A Status Update on the eMMRTG Project

Christopher S. R. Matthes
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-3255
christopher.s.matthes@jpl.nasa.gov

David F. Woerner
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-393-2000
david.f.woerner@jpl.nasa.gov

Thierry Caillat
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-0407
thierry.caillat@jpl.nasa.gov

Stanley Pinkowski
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-393-0012
stanley.pinkowski@jpl.nasa.gov

Abstract— **NASA has employed Radioisotope Thermoelectric Generators (RTGs) to power many missions throughout the past several decades. The Multi-Mission RTG (MMRTG) used on Mars Science Laboratory is the most recent generator developed, and the only spaceflight-qualified system currently available. The enhanced Multi-Mission RTG (eMMRTG) would be an upgrade of the MMRTG using the most current thermoelectric (TE) technology, and would provide the space community with a system that would have substantially higher end-of-design-life (EODL) power. The NASA RPS Program recently instantiated an eMMRTG system development project, evolving from an ongoing technology maturation effort at JPL to a project designed to mature and transition the skutterudite (SKD) TE couples and technology into an operational RTG.**

The project has made significant advances in maturing SKD technology for use in the eMMRTG, and is looking ahead to potential RTG system development. Mini-module and couple life tests have produced substantial performance data that has helped refine the couple design and support lifetime performance predictions. Additional strength and thermoelectric properties tests have been performed to verify the design specifications and robustness of the candidate TE couples. Replacing the current MMRTG couples with SKD also necessitates system design changes that must be well understood. Recent systems engineering studies have focused on minimizing risk associated with updating the flight-proven MMRTG design. Upgrading the module insulation has been shown to result in 98% lower levels of CH4/H2 outgassing products. Performance analysis has been completed using the most recent TE couple sizes in order to understand the maximum acceptable power degradation rate to achieve the required eMMRTG power of 77 W at EODL. This paper provides an update on recent SKD technology maturation efforts and the results of several systems engineering tasks that continue to pave the way for successful system development.

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1. INTRODUCTION

Radioisotope Power Systems (RPS) have supported NASA spaceflight missions for five decades, using reliable and proven technology to power historic achievements throughout our solar system and beyond. A number of RTG designs and associated thermoelectric (TE) materials have been employed for various mission types, from planetary probes to landers. The Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) is currently the only spaceflight-qualified system available to NASA missions, and designed for both vacuum and atmospheric environments.

The enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG) Project is focused on producing a block upgrade to the existing MMRTG, while sustaining the current MMRTG fabrication capability to allow NASA to be prepared for the production of future units, if needed. The eMMRTG would be based on the MMRTG design, with the following three modifications[1]:

- Substitute higher-efficiency Skutterudite (SKD) thermoelectric couples for the legacy PbTe/PbSnTe/TAGS couples.
- Add a surface oxidation layer to the heat source liner inner-surface to allow for higher hot junction temperatures in order to maximize conversion efficiency.
- Enhance the thermoelectric module insulation using aerogel.

With the modification of SKD couples, the eMMRTG would be the first RTG with new thermoelectric technology in over 30 years. This advancement would seek to improve the 17-year end-of-design-life (EODL) power by at least 50%[2]. Even with these innovative changes, the eMMRTG seeks to preserve the design heritage of the MMRTG where practical. The features and requirements maintained for the new system include the size envelope, interfaces, and mass, with a goal of offering significant increases in power over the MMRTG.

Since 2013, two separately funded and managed tasks led by NASA's Jet Propulsion Laboratory (JPL), and advised by the U.S. Department of Energy (DOE) have advanced in parallel to support development of a future eMMRTG: 1) a skutterudite technology maturation (STM) task to develop SKD couples and transfer the technology to industry; and 2) eMMRTG systems engineering [3] to support STM tasks and deliverables. Teledyne Energy Systems Incorporated (TESI) in Hunt Valley, Maryland and Aerojet Rocketdyne (AR) in Canoga Park, California are the contracted industry partners on the project. The eMMRTG Project is managed out of NASA Glenn Research Center (GRC), and takes the STM and systems engineering tasks under its umbrella to carry out the remainder of the technology maturation phase as the project moves toward system development.

2. PROJECT STATUS

The project is currently in the second of a three-phase technology maturation process depicted in Figure 1. This process is overseen by the NASA Radioisotope Power Systems (RPS) Program Office. Each phase of the process initiates with the successful completion of a Technology Decision Gate review. Phase A was completed in 2015 by passing Gate 1, which was focused on demonstrating the manufacturability of the SKD materials. Phase B is currently underway, in which the SKD couples are further matured along with the module insulation design, and 12-couple mini-module life testers (MMLTs) are put on test to begin to collect long-term performance data for the couples. The primary purpose of this phase is to establish manufacturing readiness for development of a full-scale 48-couple module. A successful Gate 2 review in January 2019 would commence Phase C, which would be focused on technology refinement and scaling up production to system development beyond Gate 3.

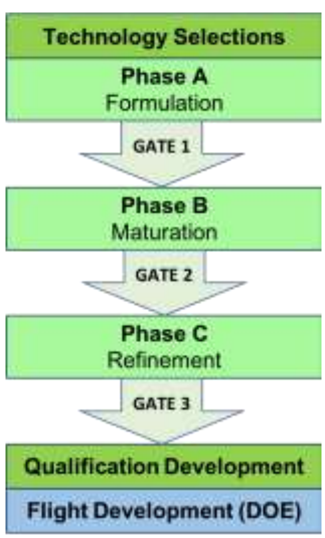

Figure 1 eMMRTG Project Technology Maturation Phase

Following a successful Gate 3 review, currently scheduled for December 2019, the project would transition to a generator development task in partnership with DOE's Idaho National Laboratory (INL). This phase would begin with the fabrication of a qualification unit, followed by flight unit development for a potential future mission.

While the overall design of the generator is identical to the MMRTG, the eMMRTG Project is taking on significant module-level design changes. Upgrading the thermoelectrics to SKD couples introduces risk that must be characterized and mitigated.

A comprehensive test program is underway to collect valuable data that will inform lifetime performance prediction and provide insight into the risks associated with implementing new thermoelectric technology. The project has a collection of currently-used and planned test articles at increasing levels of fidelity, each serving a distinct purpose and working to improve readiness for eventual production of a potential TE generator qualification unit. Dual-couple life testers (DCLT) provide long-term performance data, and are easily replicated with different temperature conditions. A number of SKD couple configurations, distinguished by their TE materials, metallization layers and bonding techniques have been tested in the DCLTs in order to provide the data needed to down-select the couple designs for further development. Two couple configurations remain as candidates, and future testing is focused on maturing and developing these designs. Mini-module life testers possess modules of 12 couples encapsulated in hybrid-Microtherm infiltrated with critical point-dried aerogel (CPDA) (HMIC) insulation in order to test the couples in a more relevant environment. Beyond Gate 2, a full-scale 48-couple module tester is planned in order to provide the highest fidelity test conditions prior to production of a qualification unit. Each of these test conditions provide long-term performance data as well as destructive physical analysis (DPA) results that provide further insight into any degradation mechanisms present. Gate 2 will also serve to down-select the final couple design for the eMMRTG. This selection will be informed by DCLT and MMLT performance data and DPA results that point to the most viable couple configuration. Additional testing, including couple strength, thermal cycling, dynamic load, and thermoelectric properties testing will also be used to inform this decision. The selected couple design will be used to populate the 48-couple module tester and future MMLT and DCLT tests in order to generate a complete set of lifetime performance prediction data.

3. DESIGN CRITERIA

The driving power requirement for the eMMRTG is to achieve an electrical power output of 77 W at EODL when operated at a voltage of 34V, a beginning-of-life (BOL) thermal inventory (Q_{th}) of 1952 W, and a fixed fin-root temperature of 157°C. Lifetime performance analysis, therefore, is generally anchored by these conditions. Operating at a different fin root temperature will alter the hot junction temperature of the SKD couples and thereby affect the power degradation over the lifetime of the generator. Degradation mechanisms include changes in electrical resistance, thermal interface conductance, SKD sublimation, and thermal insulation properties changes, which are all inputs to the lifetime performance prediction analysis. Higher operating temperatures generally result in greater BOL power output, but typically advance the degradation mechanisms. Additionally, the generator reaches peak power output at a particular operating voltage, so operating higher or lower than that voltage point will similarly affect the hot junction temperature, and therefore the power output level and degradation rate. For this reason, an allowable flight envelope (AFE) has been established for the eMMRTG, defined by a range of fin-root temperatures and voltages. The AFE is shown in Figure 2. This particular range of voltages and temperatures was devised according to mission analyses, which defined the expected operational needs for an eMMRTG system.

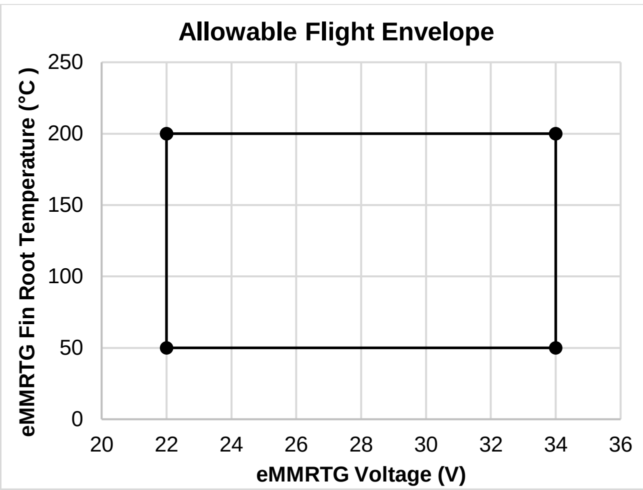

Figure 2 Plot of eMMRTG Allowable Flight Envelope. eMMRTG voltage can be varied from 22V to 34V and fin-root temperature can be varied from 50°C to 200°C in flight.

Because the hot junction temperature of the SKD couples will vary according to the operating conditions, the power degradation rate will differ according to the particular location within the AFE. For this reason, the worst-case operating condition is identified as the upper right-hand corner of the envelope (T_{fr}=200°C, V=34V), where the fin-root temperature is highest and the voltage is furthest from the peak power point. Under these conditions, the hot junction temperature can be expected to be approximately 600°C at BOL. For the EODL power requirement of 77W, the corresponding conditions yield an average hot junction temperature of about 550°C.

4. Systems Engineering Studies

The design changes to the flight-proven MMRTG design introduces risk that needs to be well understood and characterized. Recent systems engineering studies have focused on mitigating risk associated with updating the heritage design. The following paragraphs offer a summary of a number of these studies that have occurred over the past couple years.

Liner Oxide Layer Testing. As previously mentioned, a surface oxidation layer will be added to the heat source liner inner-surface to increase its emissivity in order to lower the temperature of the Min-K insulation support system at the ends of the heat source cavity. This task aimed to verify that the oxide layer on the liner inner diameter is feasible by retiring the fabrication risk and long-term stability risk. The heat source liner is composed of two separate segments. This effort involved modifying the liner segment fabrication process to include the oxide layer on the inner diameter of the liner, and verifying the integrity of the segments fabricated to the new procedure. The test articles underwent proof, leak and thermal cycle testing with a post-test inspection of the oxide layer. Emissivity of the oxide layer was also measured. Fabrication of the liner segments with an oxide layer on both the inside and outside surfaces was successfully developed and demonstrated. Solution annealing of the rough machined liner segments facilitated machining of the segments to final dimensions without intermediate heat treat steps. Grit blasting provided uniformity in the surface finish. Cleaning standards were employed to limit the blemishes in the oxide layer, and produced successful results. No distortion or "potato chipping" was evident following the high temperature heat treat. Solution annealing the rough machined part and removing similar amounts of material from the inner diameter and outer diameter during final machining are believed to be contributors to limiting distortion. Carefully controlled heat-up and cool-down rates were successfully employed. Lessons learned from this successful risk reduction activity have been recorded and AR will be ready to fabricate this liner segment design for future eMMRTG programs.

Independent liner emissivity measurement. TESI procured a third-party measurement of liner emissivity using flat coupons fabricated from the material removed from the inner diameter of the liner, following Electrical Discharge Machining (EDM) of the bar stock. The eMMRTG liner finish was applied on both sides of the flat coupons, which were then tested for their total hemispherical and normal spectral emissivity. The results of this testing were utilized to calibrate the normal spectral emissivity results of the liner segments. Results indicate that the normal spectral emissivity is increasing slightly with time, but this is likely due to the aging process having residual amounts of oxygen. The total hemispherical results show no trend in emissivity with time. The constant temperature emissivity value has been updated from the previously reported value for use in the generator performance models. A grit-blasted coupon without any liner emissivity coating was tested as a comparison to these results. This coating-less coupon represents the absolute worst-case situation where all of the oxide layer is completely removed. The grit-blasted-only coupon was tested for its total hemispherical emissivity, and was measured to be approximately 0.50, with the coated coupon measured to be about 0.77 in the temperature range of interest. These emissivity values are in contrast to a value of approximately 0.35 for a pristine Haynes 25 surface. System studies by TESI indicate that end insulation temperatures are more sensitive at lower liner surface emissivity values, meaning that raising the surface emissivity from 0.35 to 0.5 has a greater impact on lowering the Min-K temperature than the difference between 0.5 to 0.77. In short, the addition of the liner oxide layer was found to achieve emissivity values that would allow it to be effective at meeting its intended purpose of moderating the insulation support system temperatures.

Evaluate Hard-Coated Aluminum Module Bar Replacement. This task had the objective of evaluating the impact of using hard-coated aluminum module bars as an additional electrical isolation layer. This modification was considered likely to eliminate or minimize the possibility of a shorting problem that occurred on the MMRTG flight unit. This task aimed to evaluate thermal expansion, system weight gain, document necessary design changes, estimate temperature gradients, and estimate electrical performance of an eMMRTG using these new module bars. The results of this investigation showed that in general, switching from beryllium to hard-coated aluminum module bars yields minor changes to the generator design. The most notable difference is that aluminum increases the generator weight by approximately 1.0 kg. The increased thermal expansion of aluminum does not appear to present any risks to the tolerances of the piston gaps. The thermal conductivity of hard-coated aluminum has a negligible effect on the predicted power at BOL; however, the increase in internal temperatures may drive small changes in the couple cross-sectional area and slightly reduce the BOL electrical power.

Structural Assessments for Using the MMRTG Configuration Liner, Bellows, Housing Elements, and Housing Fins for the Intended eMMRTG Application. The objective of this task was to perform updated stress analyses for the heat source liner, bellows, and external generator housing using new high-temperature creep data from Oak Ridge National Laboratory (ORNL) for Haynes 25. This analysis was to consider the highest temperature corner of the allowable flight temperature (AFT) envelope (T_{fr}=200°C, 34 V). The Haynes 25 creep rupture property data set has now been updated for the eMMRTG application with additional test data documented. Stress assessments with the updated creep rupture property data show that the MMRTG configuration Haynes 25 liner and bellows are structurally acceptable for the intended eMMRTG operation. Grit blasting and oxidizing the surface of the Haynes 25 has been shown to increase the yield strength of the material, indicating that the creep rupture analysis is conservative in this case. All aluminum 2219-T851 elements of the MMRTG configuration housing system, including the housing main body, the mounting end cap, the fueling end cap, and the preload plate, are structurally acceptable for the intended eMMRTG operation. The MMRTG configuration housing fins have been found to be structurally acceptable for the intended eMMRTG operation.

eMMRTG Performance Analysis Updates and Analysis. Performance estimates were made using a thermal inventory range of Q_{th}=244-256W per general purpose heat source (GPHS) block at launch. Additionally, evaluations were made of temperatures and power at BOL, beginning-of-mission (BOM) and EODL. Time periods of both 1.5 and 3 years between BOL and BOM were considered. Performance estimates were updated based on current best information, including thermoelectric properties, thermoelectric leg dimensions, electrical interface resistances, hot and cold shoe resistivity, insulation configurations, etc. A key objective of this analysis was to evaluate performance at both BOM and EODL. Performance was evaluated over the range of hot junction (T_{HJ}) temperatures at BOM. SKD degradation effects vs. T_{HJ} and SKD module (material and interfaces) degradation rates vs. temperature were incorporated into the models when available. Utilizing the updated material properties, new optimal leg sizes were calculated and are slightly smaller than the 2016-2017 calculated leg sizes. These new leg sizes are still larger than the originally calculated leg sizes from 2013. If the BOL electrical interface resistivity is the nominal value predicted according to the deep space case, (Q_{th}=1952W, Voltage=34V, T_{fr}=157°C) BOL generator power output is found to be 139.0 W. This result allows for an average power output degradation of 3.48% per year, including fuel degradation, in order to achieve the required 77W at end of design life, with a 17-year design life. Monte Carlo results indicate that the uncertainty in the power output as a result of the model inputs is decreasing as compared to similar runs in 2016. This result is a good indicator that overall system variability is reducing as the manufacturing processes mature.

Test Electro-Static Discharge (ESD) effect on eMMRTG paint. The objective of this task was to determine if the thermal control coating on the MMRTG meets the electrostatic discharge requirement in the eMMRTG System Requirements Document (SRD). Resistance measurements were obtained on coated coupons having undergone the standard emissive coating application procedure, and they were determined to meet the electrostatic discharge requirement of the eMMRTG SRD. The resistivity-thickness product of this coating is 3 orders of magnitude below the maximum allowable value of $2x10^9$ Ω-cm^2.

HMIC Outgassing. The University of Dayton Research Institute (UDRI) was contracted to assist JPL in understanding the outgassing behavior of HMIC so that the effect it has on the gas phase of the eMMRTG can be determined. The overall quantity of gases produced by the HMIC, including CO, CO, CH_4, and H_2O, was found to be dramatically smaller than the quantity produced by hybrid-Microtherm infiltrated with aerogel (HMIA) insulation. Quantitatively speaking, the HMIC appears to produce 98% less CH_4/H_2 than HMIA. Figure 3 presents both the HMIC and HMIA data as a function of time, and it is clear that HMIC produces very little gas by comparison.

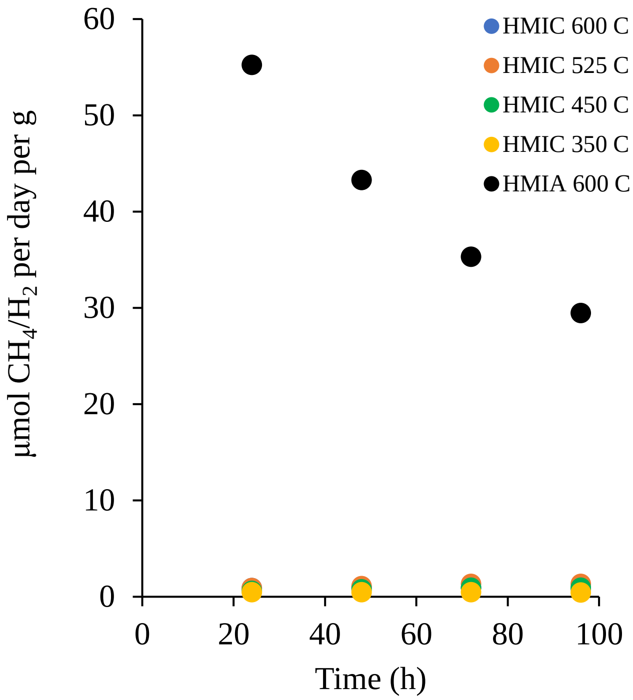

Figure 3 Comparison of CH_4/H_2 outgassing per gram of insulation from HMIC and HMIA. Data represent the amount of gas collected over a 24 h period (i.e. the data is not cumulative). Ratio of CH_4 to H_2 is ~2:1.

This result indicates that the amount of CH_4 that would be expected to be found inside the eMMRTG is very low. Results from early MMLT tests, which contained HMIA, indicated that there was ~7000 ppm of CH_4 in the test chamber. Use of HMIC, therefore, should reduce the amount of CH_4 down to 100-200 ppm.

The outgassing rate of water from HMIA is also of interest for determining the oxidation risk to the eMMRTG. The rate of water outgassing from HMIA was measured during the CH_4/H_2 outgassing experiments. Figure 4 shows the rate of water release as a function of time and temperature. This data shows that the amount of water that outgasses from HMIC does not change appreciably compared to HMIA. It also shows that the rate of water outgassing is always < 1 μmol per gram of insulation per day, with production values dropping off fairly quickly towards zero. This number is very small, and it helps reduce the oxidation risk for the eMMRTG.

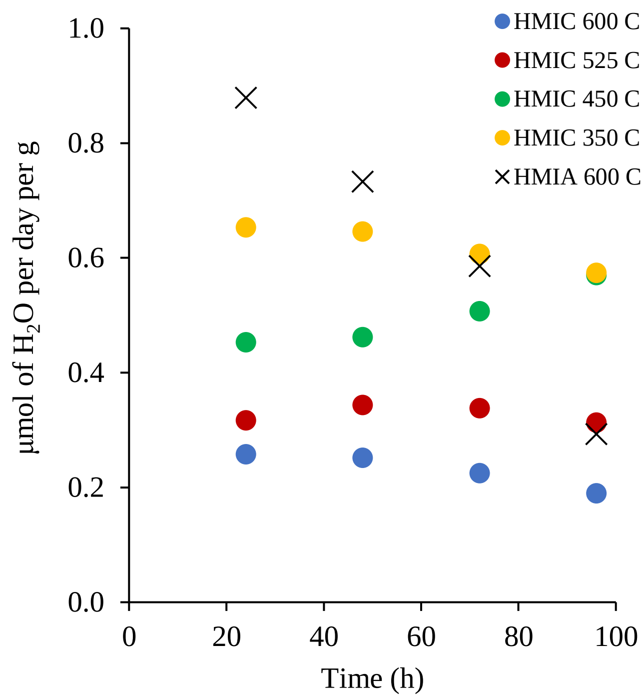

Figure 4 Comparison of H_2O outgassing per gram of insulation from HMIC and HMIA. Data represent the amount of gas collected over a 24 h period (i.e. the data is not cumulative).

5. Summary and Path Forward

The eMMRTG Project has made considerable progress in advancing the SKD couple technology for the next stages of NASA decision making. Upon successful completion of the Gate 2 review planned for January 2019, the project would move forward with implementing the couple technology into a 48-couple module. A number of tests are planned in the coming months to prepare for this next stage of the project. Vibration testing, thermal cycle testing, and dynamic load testing will be carried out along with the continuation of performance testing with the dual-couple and mini-module life testers.

As the project moves toward potential generator-level system development, it is planning to transition to a new contract structure managed by NASA in partnership with DOE through a contract issued through INL. JPL will have technical oversight of the INL-held contract as part of the eMMRTG team managed by NASA GRC. A successful Gate 3 review would lead to a TE generator qualification unit build for a potential 2024 delivery[4]. As the project progresses, an MMRTG sustainment effort is continuing to assure that an RPS is available for future missions as needed.

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The information in this paper about future RPS is pre-decisional and is provided for planning and discussion purposes only.

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BIOGRAPHY

Christopher S. R. Matthes *received a Ph.D. in Aerospace Engineering from UCLA in 2016. He also has a M.S. from UCLA and a B.S. from Michigan State University, both in Mechanical Engineering. His thesis focused on characterizing material surface evolution in electric propulsion devices. Dr. Matthes is currently a systems engineer working in thermal energy applications and systems at NASA Jet Propulsion Laboratory, focusing on nuclear power systems. He serves as the Project Systems Engineer for the enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG) Project. He also holds a lecturer position at UCLA, where he teaches Mechanical and Aerospace Engineering Laboratory.*

David F. Woerner *has more than 35 years' experience as a systems engineer and manager at JPL including as the Launch Services and MMRTG Office Manager for the Mars Science Laboratory mission that successfully landed on Mars on August 6, 2012. He is presently the Principal Engineer for NASA's Radioisotope Power System Program. Woerner has worked at JPL on such missions as Galileo, Cassini, Magellan, Mars Pathfinder, and MSL. He was the Chief Engineer of the avionics for the Mars Pathfinder mission that successfully landed on Mars on July 4, 1996. He is the Chair of the Board of Directors for the IEEE Aerospace Conferences. He has won numerous NASA awards including earning NASA's Exceptional Service and Exceptional Achievement Medals.*

Thierry Caillat *is a principal member of technical staff at the Jet Propulsion Laboratory/California Institute of Technology. He has over 26 years of experience related to thermoelectric materials and power generation. His current research interests focus on the development of advanced thermoelectric couples and modules for integration into advanced Radioisotope Thermoelectric Generators as well as terrestrial thermoelectric power generators. Dr. Caillat has played a key role in the discovery of skutterudite materials which are now investigated worldwide and are one of the leading classes of advanced thermoelectric materials. Dr. Caillat has authored over 100 publications and holds 17 US and international patents. He has served on many US and international review committees and panels. He served on the Board of the International Thermoelectric Society from 1996 to 2011 and was its president from 2009 to 2011.*

Stan Pinkowski *is an aerospace industry veteran having worked on numerous space power, propulsion and terrestrial energy projects in various roles of program management, systems and development engineering, and business development. He spent nearly 30 years with Rocketdyne under the Rockwell, Boeing, and United Technologies companies as well as with solar thermal energy startups. Notable technologies and programs include radioisotope, nuclear, and solar power systems for thermoelectric and dynamic power. Stan is currently a Technologist with the NASA Jet Propulsion Lab in the Power and Sensor Systems group contributing to the maturation of advanced thermoelectric technology for RTGs as well as other RPS dynamic power systems. He is an alumnus of Purdue and Pepperdine Universities.*